Efficiency and Coverage Improvement of Active RFID Two-Hop Relay Systems

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Abstract—One major issue in the design of active Radio Frequency IDentification (RFID) systems is the need for increasing the coverage, since it is essential for many applications to have a large communication range. In this paper, we propose an active RFID system based on ISO/IEC 18000-7, an energy efficient RFID standard, in which a two-hop relay system is utilized. It is shown that our proposed two-hop relay system can increase the coverage of the reader. In order to increase the efficiency of the two-hop system, we propose a Participation ID (PID) two-hop system. In our modified method, active tags do not participate more than once in a collection round. Hence, the power consumption of active tags is decreased and the throughput of the system is increased. We also evaluate the performance improvement of our modified method in comparison to the existing two-hop relay systems through simulation.

I. INTRODUCTION

Radio Frequency IDentification (RFID) is an automatic identification technique by which the system uses radio frequencies to communicate between RFID readers and RFID tags. The RFID systems are categorized into three major groups in terms of their types of tags: passive, semi-passive, and active [1–2]. If a tag functions without a battery, it is classified into passive RFID systems which are smaller and cheaper than other systems for manufacturing purposes [3–4]. Instead of using a battery, these systems are empowered by the signal sent from a reader, which enables them to respond by backscattering the signal. The communication strategy for passive RFID systems are based on requesting and then responding, i.e., a reader sends an interrogation signal to all tags that are in its range and then each tag sends a response to the reader by backscattering the interrogation signal, which is a modulated version of the tag that carries information from the tag to the reader [5]. In order to improve the functionality of a passive RFID, using a battery could be helpful. Those partly battery powered systems are denoted as semi-passive RFID systems [6] and those that are completely powered by battery are known as active RFID systems [7–8]. Because of the internal power source, the RF communication range of the active RFID tags is larger than the passive ones, which improves the utility of the device. Applying a sensor to the device can also enhance its applications. Hence, active RFID systems can be used in a variety of fields such as process automation, port logistics, air logistics, maturing ecosystem technology, and vehicles [4], [9–11].

ISO/IEC 18000 – 7 is a series of standards to define the air interface for RFID devices. According to the frequency band used in the RFID systems, this standard has been divided into several parts. Its seventh part defines the air interface for active RFID systems in 433 MHz. In active RFID systems, increasing the communication coverage of the reader is an important issue since many applications need a large communication range. The ISO/IEC 18000 – 7 standard has this feature but it cannot be applied to a large-scale area. In [4], [12], a large-scale active RFID system based on the multi-hop deployment utilizing ZigBee networks were proposed to meet these limitations. Another method can be found in [13], which increases the communication range via using relay tags [14]. This increase reduces the number of expensive required readers. The drawback of using such a system is the overlapping areas of the reader and the relay tags.

In this paper, we solve the overlapping problem of using relay tags. These overlapping areas increase the collection process time, decrease the theoretical throughput, and cause the tags to waste their energy. To overcome this problem, we use one-bit Participation ID (PID), which makes the tags that are in the common communication area not to participate in a collection round more than once. This causes the tags that are able to communicate with the reader in a direct way to use the reader instead of the relay tag. In order to verify what has been proposed, we run simulations to evaluate the performance of our method.

The rest of this paper is organized as follows. We first introduce the tag collection algorithm in ISO/IEC 18000 – 7 and also the tag collection algorithm based on two-hop relay systems in Section II. Next, we describe our modified method for increasing the efficiency of a two-hop relay system which includes adding one-bit PID to the active tags in Section III. In Section IV, we present and analyze the simulation results, and finally the conclusion is drawn in Section V.
II. TAG COLLECTION ALGORITHM

In this section, we first consider the tag collection algorithm defined in the ISO/IEC 18000 – 7 standard. This system consists of one reader and some tags in the reader’s region. Next, we analyze the algorithm used in the two-hop relay system, which consists of one reader, some relay tags, and some tags.

A. Tag Collection Algorithm in ISO/IEC 18000-7 Standard

The tag collection algorithm defined in ISO/IEC 18000 – 7 uses the anti-collision algorithm based on the slotted ALOHA protocol. The frame structure is shown in Fig. 1. Before a reader performs a tag collection producer, a wakeup signal is required to awaken the tags that are in the sleep mode within the reader’s RF communication range (sleep mode is necessary to save the battery power of the tags). The wakeup signal is transmitted by the reader for a minimum of 2.5 seconds. Whenever the wakeup signal is detected, all tags enter into a ready state waiting for commands from the reader. After that, the reader collects the data from all tags by iterative collection rounds.

A single collection round is initiated by a collection command, which contains a two-byte window size message. The window size defines the total waiting time for the reader to listen to the multiple tags response. Upon receipt of a collection command, the tag randomly selects a slot and sends its response, which contains its own tag-ID, in that slot. One slot is long enough for the reader to receive a tag response. The window size that is sent by the reader is specified by

\[ \text{Window Size} = \text{Window Factor} \times 57.3^{\text{milliseconds}}. \quad (1) \]

The window factor is an integer value that is used for changing the window size. In the initial step of the tag collection process, the window factor is set to 1, and thus, the window size in the first step is fixed to 57.3\text{ms}.

As shown in Fig. 1, slots can be classified into three groups: identified slots that are filled with exactly one tag response, collided slots with two or more tags sending their responses simultaneously, and the empty slots that are not chosen by any tag. After the time of passing the window size, the reader sends a sleep command to all successfully collected tags during the collection round by using point-to-point transmission. Clearly, any tag that receives a sleep command, shifts to sleep mode and does not participate in the subsequent collection rounds. While the subsequent tag collection process is running, the reader chooses an optimum window size for the next collection round by estimating the number of remaining tags, based on the number of identified, collided, and empty slots. One slot size (S) is defined as

\[ S = \text{Response Transmission Time} + \text{Slot Guard Time}. \quad (2) \]

The response transmission time is the required time for a tag to transmit its own response packet. The size of this packet is determined by the collection command type. The slot guard time allows the reader to process the data of a received tag response and to get ready for receiving the next tag response. This guard time is fixed to be 2\text{ms} according to the standards. The slot size will be then rounded up to the next nearest milliseconds. Using the slot size, the number of slots in a current collection round \((N_S)\) can be calculated as

\[ N_S = \frac{\text{Window Size}}{S}. \quad (3) \]

The reader starts the next collection round just after completing the current one, by transmitting the collection command. This process will be continued until no additional tags are detected during three subsequent collection rounds.
B. Tag Collection Algorithm in RFID Two-hop Relay Systems

Fig. 2 shows the RFID two-hop system scenario. Interrogator (reader), active relay tags, and active tags are the elements of this system. In Fig. 3 the two-hop frame structure is depicted. After the reader transmits wake-up signal, active tags and active relay tags that are in the coverage of the reader, enter the ready state. In the next step, active relay tags forward the wake-up signal to active two-hop tags. After receiving the collection command in the same way the wake-up signal is received, these two-hop tags calculate the slot size and the number of slots in the current collection round using the received window size. Similar to the one-hop tags, the two-hop tags randomly select a slot in which to respond. Active relay tags collect all the responses from the two-hop tags and transmit these responses to the reader in the next period. After the reader finishes the current collecting round, it sends sleep command, and relay tags relay it to the other tags that are in their coverage. Therefore, the tags that have been collected successfully move to the sleep mode and do not participate in the subsequent collection round. Next, the reader starts a new collection round by transmitting the collection command.

III. MODIFIED TWO-HOP RELAY SYSTEMS BY USING ONE-BIT PID

One important problem about the RFID two-hop relay systems is the overlapping areas of the reader and the relay tags. Thus, some active tags place within the reader coverage area and one or two relay tag coverage areas – in some situations, they would place in overlapping areas of two relay tags. Fig. 4 depicts this overlapping problem. These tags have to respond at least twice, since they receive collection commands from more than one source during a collection round. These tags waste their energy and also increase the collection process time.

Another important issue is about the probability of a successful tag access. If there are \( N \) slots and \( n \) tags, the probability of having \( q \) tags in one slot can be calculated by the binomial distribution which has the form of [15]

\[
p(N, n, q) = \binom{n}{q} \left( \frac{1}{N} \right)^q \left( \frac{N - 1}{N} \right)^{n-q}.
\]

As the number of tags increases, the theoretical throughput decreases. Thus, when a tag participates in the collection process more than once, it decreases the efficiency of the system. Moreover, when a tag wants to send its data to the reader by using a relay tag, the data should be sent two times: from the tag to the relay tag, and then from the relay tag to the reader. This process decreases the throughput and is time-consuming. Thus, in the situation that a tag can send its data directly or by using a relay tag, the best choice is to connect directly with the reader.

In our modified two-hop relay system, one-bit PID is added to all tags in order to prevent the tags from participating in a collection round more than once. When a sleep tag receives the wake-up signal, it moves into the ready state and set the PID to zero. Then, when the tag receives a collection command, it changes the PID into one, and does not change it until sending its data to the reader. When the PID equals to one, the corresponding tag is in the process of responding. As long as this holds, which corresponds to the time between receiving and responding to the collection command, the tag is not sensitive to any other collection commands from other sources, i.e. relay tags. Finally, when the tag responds and sends its data, the PID is changed to zero. As a result, if the responding is not successful, the tag can participate in the next collection round. Using this method will allow the active tags that are placed in the overlapping areas of the reader and
relay tags to communicate with the reader directly. When they receive the first collection command from the reader, they are not sensitive to other collection commands from the relay tags. Fig. 5 represents the flowchart for active tags according to the proposed method.

IV. SIMULATION RESULTS

In this section, we show the simulated results to evaluate the performance of the proposed protocol. Since the coverage of the forward link is shorter than the reverse one, the total system coverage is determined by the forward link. For the active RFID system, the coverage of the forward link of the reader is about 131 meters, and its relay tag is 26 meters. Thus, in our simulation, the communication coverage is about 157 meters. The number of relay tags for achieving this coverage is assumed to be 16. We use two different distributions in order to perform the simulations: the normal and uniform distributions. The normal distribution has been chosen for the active tags because in this situation we can place a single reader in the center of the active tags and cover almost all of them by using the relay tags and without additional readers. On the other hand, if the active tags are distributed in the uniform way and the environment is a little more than our reader coverage, we can use relay tags to cover all of the active tags without using additional readers.

Fig. 6 depicts the number of tags that are placed into the communication area which is common between the reader and one relay tag for normal distribution in percentage. It is clear in this figure that as the number of tags increase, more of them have to respond to the relay tags and the reader in a collection round. But with our proposed method, these tags only respond to the reader. Fig. 7 shows the same result for the uniform distribution. These figures reveal that the percentage of the tags which place in a common area in each distribution is almost constant. For the normal distribution, the results are 8.2, 9, 9.3, and 9.5 percent by variances 85, 95, 105, and 115, respectively. For uniform distribution the percentages are 16.8, 15.58, 14.77, and 13.8 when the tags are in (0,140), (0,150), (0,160), and (0,170) intervals, respectively.

In Fig. 8 we illustrate the number of tags that use the relay tags in a two-hop relay system with and without using the PID method for the normal distribution. Fig. 9 represents the same result for the uniform distribution. As it is mentioned in the previous section, when a tag uses the relay tag to send its data to the reader, the data should be sent twice: from the tag to the relay tag and then from the relay tag to the reader. As these figures show, the numbers of tags that use the relay tags decrease in our modified method since the tags that can use both the reader and the relay tags, only use the reader. Thus, the efficiency of the system in terms of collection process time, battery usage, and theoretical throughput increases.

For analyzing the improvement in time efficiency of the
proposed method, we consider the proportion of 2-hop transmission process time for an active tag to 1-hop one. Although this proportion depends on the number of active tags and the number of collection rounds, we can consider it almost constant and with the ratio two to one. The Improvement in Time Efficiency of PID method can be defined as

\[ I_{\text{TimeEfficiency}} = \frac{T_{\text{withoutPID}} - T_{\text{withPID}}}{T_{\text{withPID}}} \times 100(\%) \] (6)

\[ T \text{ is given by} \]

\[ T = \frac{(N_1 \times 1) + (N_2 \times 2)}{N_1 + N_2} \] (7)

where \( N_1 \) and \( N_2 \) are the numbers of active tags that use 1-hop and 2-hop transmission, respectively.

The Improvement in Time Efficiency defined by (6) is shown in Fig. 10 and Fig. 11 for normal and uniform distributions, respectively. Fig. 10 reveals that by using PID method for the normal distribution the Time Efficiency of the two-hop system averagely increased by 10.9, 11.9, 12.5, and 12.7 percent by variances 85, 95, 105, and 115, respectively. For the uniform distribution, according to the Fig. 11, the percentages are 18.1, 15.7, 14.3, and 14.2 when the tags are in (0,140), (0,150), (0,160), and (0,170) intervals, respectively.

Furthermore, we define the Improvement in Throughput Efficiency for analyzing the throughput of the proposed method, which is given as follows

\[ I_{\text{ThroughputEfficiency}} = \frac{1}{16} \sum_{n=1}^{16} \frac{P_{n2} - P_{n1}}{P_{n1}} \times 100(\%). \] (8)

\( P_{n1} \) defines theoretical system throughput for relay tag number \( n \) without using the PID method according to (5). \( P_{n2} \) defines the same numeric value when we use the PID method. For the normal distribution the throughput of the system is averagely improved by 14.4 percent and for the uniform distribution the percentage is 9.9.

V. CONCLUSION

In this paper, we presented a PID method for the performance improvement in the RFID two-hop relay systems. In our modified algorithm, active tags only respond to one source, reader or relay tag, in a collection round and those active tags that can respond directly to the reader, do not use the relay tags. Hence, the power consumption of the active tag is reduced. As a result of decreasing the number of tags that use the relay tags, the system efficiency in terms of collection process time and theoretical throughput improves.

To verify what has been claimed, some simulations have been done with two different distributions: the normal and uniform distributions. We investigate the performance of the proposed method with the existing one for these distributions through the analyses of time efficiency and throughput efficiency. Also we observed that without using the PID method in two-hop relay systems, significant percentages of tags participate more than once in a collection round.

REFERENCES


